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Measured and predicted performance of prefabricated vertical drains (PVDs) with and without vacuum preloading

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ABSTRACT

This paper presents the effectiveness of vacuum preloading in accelerating the consolidation of PVD improved soft Bangkok clay by comparing with the corresponding results without vacuum preloading. Laboratory tests were conducted using a large scale consolidometer having diameter of 300 mm and height of 500 mm with reconstituted specimens installed with prefabricated vertical drains (PVD) with and without vacuum preloading. In addition, field data were collected from Second Bangkok International Airport (SBIA) site improved by PVD with and without vacuum pressures. Analyses were carried out to compare the compressibility parameters (C_h and k_h/k_s) by back-calculation of laboratory and field settlements using Hansbo (1979) method. From the laboratory tests, the horizontal coefficient of consolidation (C_h) values from reconstituted specimens were 1.08 and 1.87 m^2/yr for PVD without and with vacuum pressure, respectively and the k_h/k_s values were 2.7 for PVD only and 2.5 for vacuum-PVD. After the improvement, the water contents of the soft clay were reduced, thereby, increasing its undrained shear strengths. Similarly, the field data analysis based on the back-calculated results showed that the k_h/k_s were 7.2 and 6.6 for PVD without and with vacuum, respectively. The C_h values increased slightly from 2.17 m^2/yr for PVD only to 3.51 m^2/yr for vacuum-PVD. The time to reach 90% degree of consolidation for soils with vacuum-PVD was one-third shorter than that for soils with PVD only because of higher C_h values. Thus, the addition of vacuum pressure leads to increase horizontal coefficient of consolidation which shortened the time of preloading. The PVDCON software was found to be useful to predict the settlements of the PVD improved ground with and without vacuum preloading.

1. Introduction

The main purpose of this paper is to evaluate the effectiveness of PVD soft ground improvement with vacuum preloading by comparing with the corresponding results with equivalent surcharge preloading without vacuum pressure. One of the cheapest soft ground improvement methods is by drainage using prefabricated vertical drains (PVDs) to reduce the time required for consolidation of soft subsoil. PVDs are artificial drainage paths made of geosynthetics inserted into the soft ground to shorten the drainage path, and thereby, shorten the consolidation time. Usually, a surcharge load equal to or greater than the expected loading is applied over the soil surface to generate the necessary hydraulic gradient needed for vertical drainage through the PVDs. Application of PVDs method is widely used in soft ground improvement (Shen et al., 2005; Chai et al., 2006a,b; Abuel-Naga et al., 2006; Rowe and Taechakumthorn, 2008) The instability problem of the surcharge embankment dictates the height and slope of the embankment. The PVD improvement with surcharge embankment can be combined with vacuum pressure to decrease the problem of embankment instability, to reduce fill material, to accelerate the rate of consolidation and to shorten construction periods. The vacuum consolidation was first proposed by Kjellman (1952). The studies of vacuum induced consolidation continued up to the present (Holtz, 1975; Choa, 1989; Cognon et al., 1994; Bergado et al., 1998; Tang and Shang, 2000; Indraratna et al., 2004, 2005; Chai et al., 2006a,b; Chai et al., 2005; Bergado et al., 2006; Rujikiatkamjorn and Indraratna, 2007; Rujikiatkamjorn et al., 2007, 2008; Walker and Indraratna, 2006, 2009; Saowapakpiboon et al,

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2008a,b). Vacuum consolidation preloads the soil by reducing the pore pressure while maintaining constant total stress instead of increasing the total stress. The effective stress is increased due to the reduced (less atmospheric) pressure in the soil mass. The net effect is equivalent to an additional surcharge to ensure early attainment of the required settlement and increased shear strength resulting in increased embankment stability with subsequent rapid improvement in the soft clay foundation.

2. Laboratory test using PVDs with and without vacuum

2.1. Test specimens

The soil samples used in this study were obtained from a site located at the Second Bangkok International Airport (SBIA) or Suvarnabhumi Airport which is located at Samut Prakarn Province of Thailand, located 30 km southeast of Bangkok. The soft clay samples were collected from 3.0 to 4.0 m depth and placed in covered containers. Table 1 tabulates the physical properties of the soft Bangkok clay samples. The PVD material used was CeTeau drain (CT-D911). The PVD properties are summarized in Table 2.

The study was conducted on reconstituted clay specimens. The reconstituted sample was prepared by applying a consolidation pressure to the remolded sample. The remolded sample was made by adding a sufficient amount of water until its water content was greater than its liquid limit. The sample was then thoroughly mixed in a mechanical mixer and transferred in layers into the testing container. At each layer, the air bubbles were eliminated by using a vibrator. The soil specimen was consolidated under 50 kPa vertical stress in a large consolidometer until 90% consolidation was achieved determined using Asaoka's method. The method of Asaoka (1978) is commonly used to estimate the magnitude of final settlement and the degree of consolidation.

2.2. Large consolidometer

The large scale consolidometer consists of a steel cylindrical chamber 10 mm thick with an inner diameter of 305 mm and height of 500 mm placed over circular steel base plate as shown in Fig. 1. Silicon grease was applied to the inside of the cylinder camber to reduce friction between inner surface of consolidometer chamber and load transfer plate at the top. Geotextile was placed on top of soil specimen. Vertical load was applied through a loading piston at the top of soil specimen using load transfer plate thickness of 50 mm which was connected to a loading arm of the consolidometer with ratio of 5. The schematic diagram of the apparatus is shown in Fig. 2.

2.3. Vacuum generator

The vacuum pressures that were applied to the consolidometer chamber were generated from two vacuum pumps and then stored in a vacuum tank which has a maximum capacity of −120 kPa. The tank consists of a controlling board (Fig. 3a) for adjusting the vacuum pressure to the consolidometer chamber. The vacuum pressure of −50 kPa was applied to the consolidometer chamber through the top of the water container (Fig. 3b). The vacuum tank has timer to control the time of pumping and control vacuum pressure not to exceed the capacity of the vacuum tank.

Table 1
Physical properties of soft Bangkok Clay.

Liquid limit (%)	102.24
Plastic limit (%)	39.55
Water content (%)	112.69
Plasticity index	62.69
Total unit weight (kN/m^3)	14.70
Specific gravity	2.66

Table 2
Summary of CeTeau drain properties (CT-D911).

Drain body	Configuration	┝┿┿┿┿┿┿┥
	Material	Polypropylene
	Channels	44
Filter jacket	Material	Polypropylene
	Colour	grey
Weight (g/m)		78
Width (mm)		100
Thickness (mm)		3.5

2.4. Vane shear apparatus

A laboratory vane shear apparatus, capable of measuring shear strengths at different locations and depths, was used to determine the undrained shear strengths before and after the tests. The vane blades, made of stainless steel, were 20 mm in diameter and 40 mm in height. It was attached to an adjustable stainless steel rod that can be adjusted to locate measurement points within the soil specimen. The maximum torques were measured electronically for each test point. The vane shear tests were done at radial distances of 25 mm, 50 mm and 100 mm, respectively, at 3 different depths.

2.5. Consolidometer test program

The reconstituted specimen in the large consolidometer was consolidated with PVD only under a vertical stress of 100 kPa. Another reconstituted specimen was consolidated with PVD under a vertical stress of 50 kPa combined with −50 kPa vacuum pressure. The pressures were applied and vertical displacement was measured immediately after PVD installation. The settlement of both specimens was monitored until the 90% degree of consolidation was achieved using the method of Asaoka (1978). Afterwards, the undrained shear strengths and water contents were determined before and after PVD improvement with and without vacuum at the radial distances of 25 mm, 50 mm and 100 mm, respectively.

Fig. 1. Large scale consolidometer apparatus.

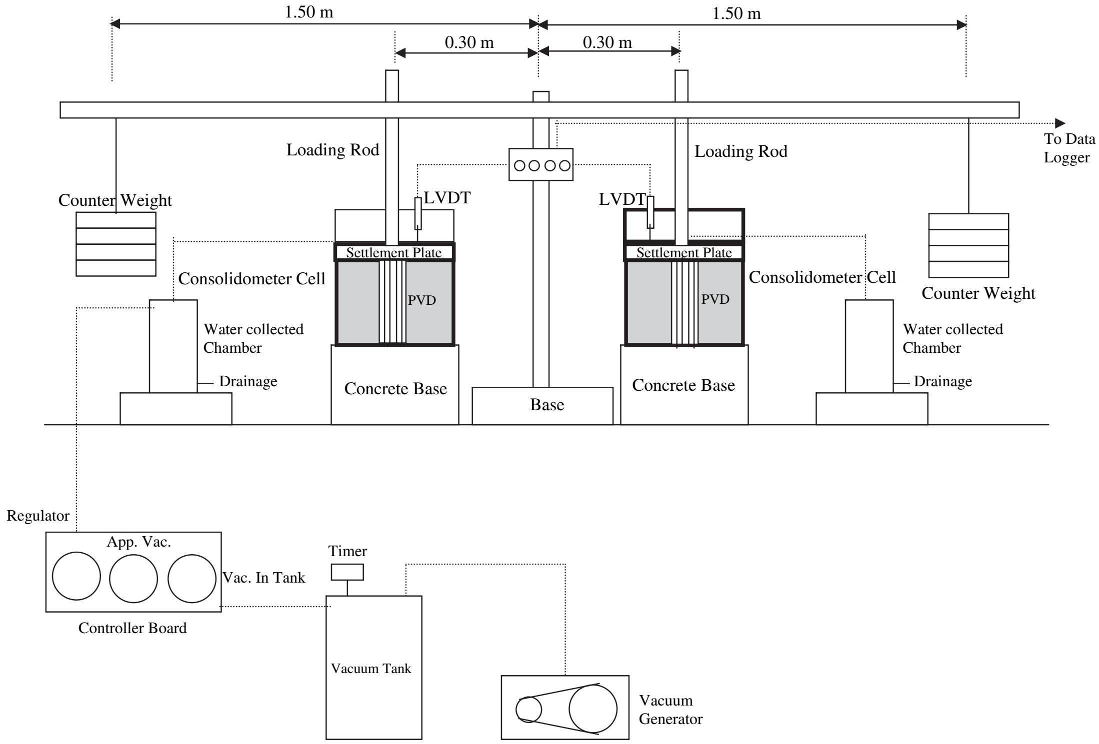

Fig. 2. Schematic of large scale consolidometer.

3. Field test using PVDs with and without vacuum pressure

3.1. Site investigations and field construction

Both vacuum-PVD and conventional PVD system at Suvarnabhumi Airport, Thailand were reported by COFRA (1996). The soil profile at the site can be divided into 8 sublayers as shown in Table 3 and it consists of a 2.0 m thick weathered clay layer overlying a very soft layer which extends from 2.0 m to 10.0 m depth. Underneath the soft clay layer of 3.0 m thickness, a 3.0 m thick medium clay layer can be found. The light-brown stiff clay layer can be encountered at 15.0–30.0 m depth. The groundwater level was

Fig. 3. (a) Vacuum tank controller board. (b) Water container to collect water from consolidometer chamber.

Table 3
The stratigraphy.

Present surface	0.00 m	
Water level	−0.50 m	
Type	Top layer(m)	Bottom layer(m)
Top layer, weathered clay	0.00	−2.00
Very soft clay 1	−2.00	−5.00
Very soft clay 2	−5.00	−10.00
Soft clay	−10.00	−13.00
Medium stiff clay	−13.00	−15.00
Stiff clay 1	−15.00	−17.00
Stiff clay 2	−17.00	−20.00
Stiff clay 3	−20.00	−30.00

Table 4
The compressibility consolidation parameters.

Type	Unit weight (kN/m^3)	Compressibility			POP (kPa)	C_v_theory (m^2/yr)
		RR	CR	C_a		
Top layer, weathered clay	18.50	0.035	0.350	0.014	45	–
Very soft clay 1	13.80	0.050	0.500	0.020	37	0.79
Very soft clay 2	14.00	0.042	0.420	0.017	59	0.79
Soft clay	15.00	0.040	0.400	0.016	100	0.79
Soft to medium clay	15.70	0.030	0.300	0.012	110	0.79
Stiff clay 1	18.50	0.008	0.080	0.003	300	–
Stiff clay 2	19.00	0.008	0.080	0.003	500	–
Stiff clay 3	20.40	0.000	0.000	0.000	500	–

found at about 0.50 m depth. In Table 4, the maximum past pressure (σ'_{vm}) is derived from the given OCR value taken as an average value of each layer. The soil profiles within the site are relatively uniform with some small variations in the soil thickness. The typical soil properties along with soil parameters are summarized in Fig. 4 taken from Bergado et al. (2002).

In the conventional PVD method, the PVD was installed to 10 m depth with a spacing of 0.85 m and arranged in a triangular pattern. This method had the embankment height in 4.3 m with loading in 2 stages. Typically, a 2:1 side slope was used for the low embankment with height less than 2.5 m. However, a 4:1 side slope was adopted for the high embankment to reduce the effect from erosion due to rainfall. The high embankment is usually constructed along with counterweight berms for stability purpose. Several types of monitoring instruments were used, including settlement plates, settlement benchmark, deep settlement gauges, piezometers, inclinometers and observation wells as shown in Fig. 5b.

For the vacuum-PVD method, the PVD was installed into 10 m depth with a spacing of 0.85 m and arranged in a triangular pattern. The instrumentation equipments were installed to monitor the field behavior. For the vacuum-PVD, similar instrumentation equipments were installed to monitor the field behavior. The locations of the inclinometers, piezometers and the settlement plate are shown in Fig. 6b. The following boundary conditions were used in the design of vacuum-PVD: installation time of drains of 2 months, maximum pumping time of 8 months, vacuum pressure of −60 kPa at 5 m depth, depth or length of PVD of 10 m below ground surface and 60% consolidation requirement. The embankment was 2.8 m high with unit weight of 18 kN/m^3. The embankment was constructed in two phases, namely: Phase 1 (1.5 m height, day 0) and Phase 2 (1.3 m height, day 14). The load–time relation of PVD improvement without and with vacuum are shown in Fig. 7a and b.

3.2. *Settlement predictions of field test using PVDs with and without vacuum*

The final settlement was calculated using the Asaoka (1978) graphical method. This method is based on the field monitored data. The horizontal coefficient of consolidation, C_h, was also back-calculated at different periods depending on the time of PVD installation. Before the PVD installation, the vertical drainage was mainly assumed in the calculation of the degree of consolidation. After the PVDs installation, the horizontal drainage mainly governed in the calculation of the degree of consolidation.

The computer software called PVDCON, based on one-dimensional finite element analysis, was used to predict the consolidation

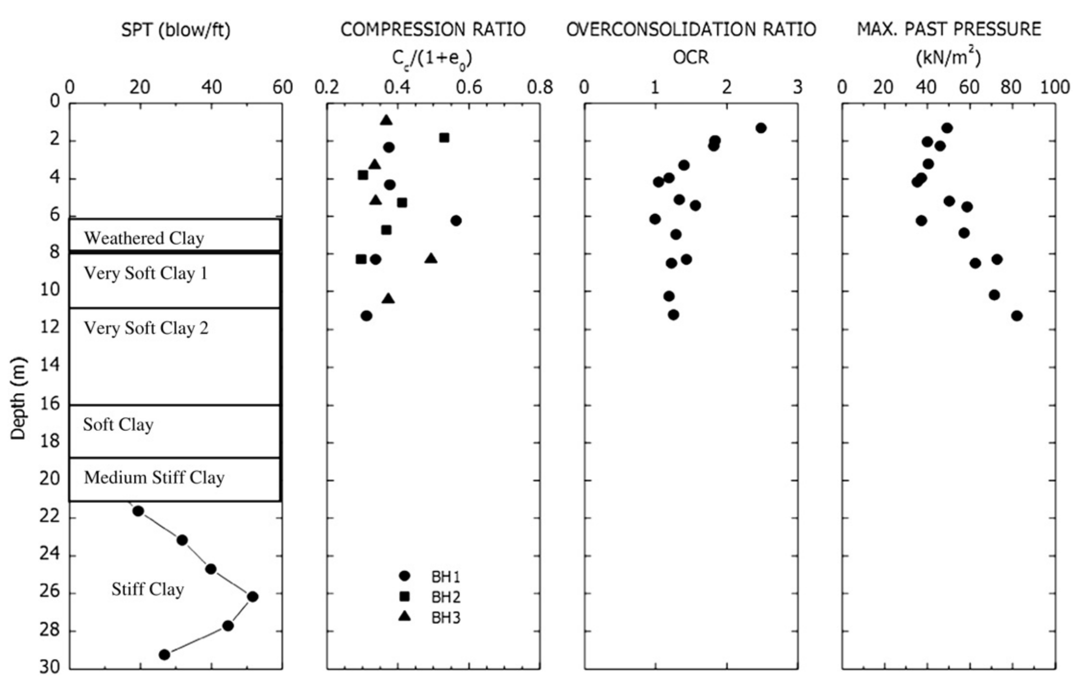

Fig. 4. Soil parameters of SBIA project (Bergado et al., 2002).

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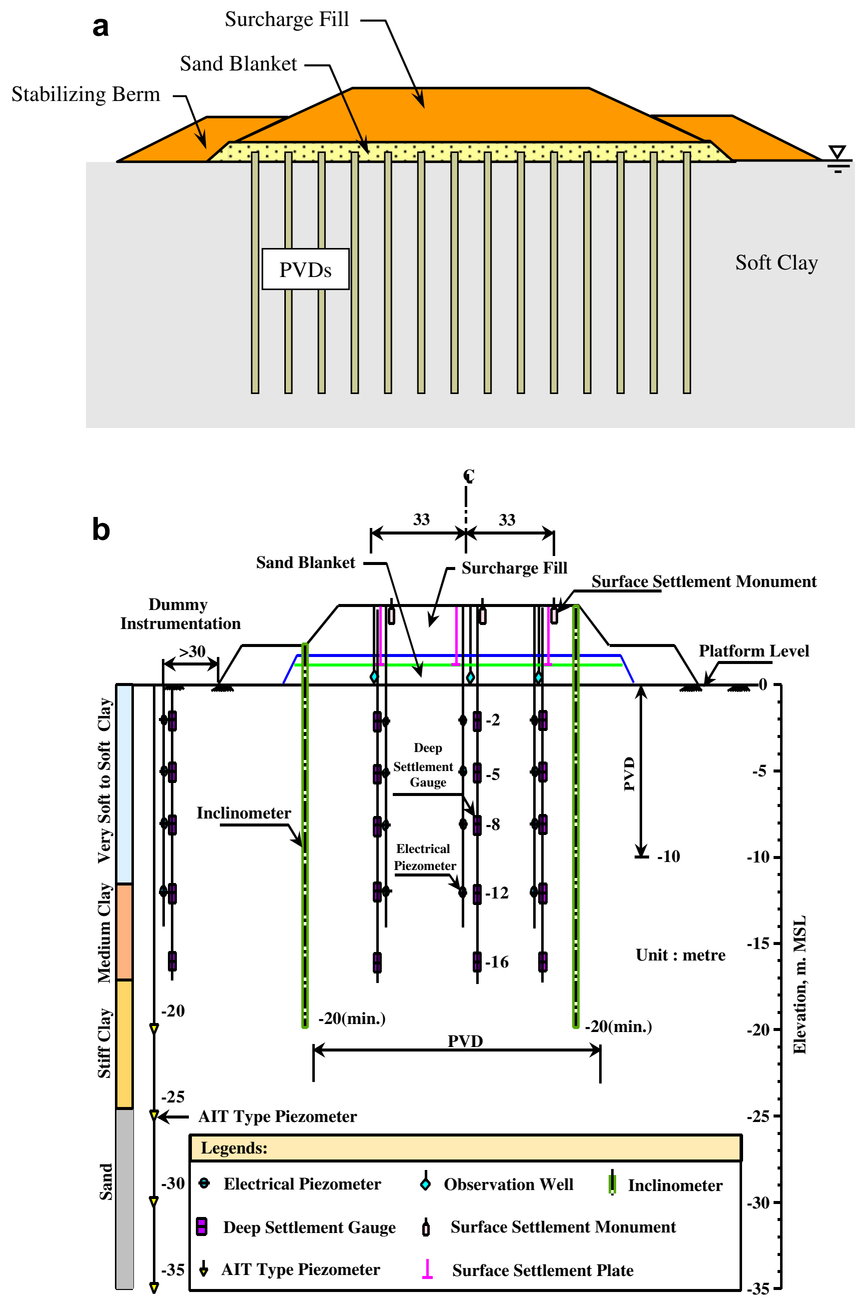

Fig. 5. (a) Cross-section of conventional PVD method. (b) Monitoring instruments of conventional PVD method.

settlement of PVD improved soft clay with and without vacuum preloading (Chai and Miura, 2000). The PVDCON can handle the problems related to multi-layered soil strata, and the computer software settlement-time plot can be obtained at different depths. For this settlement analysis, the subsoil was divided into 5 layers (see Table 4 and Fig. 4) and the whole surcharge fill was divided into different loading stages. The soil parameters at the site are summarized in Table 5. The design parameters of PVDs with and without vacuum for settlement analysis are tabulated in Tables 6 and 7, respectively.

3.3. Back-calculation C_h values

From the settlement observation, Magnan (1983) has modified the observational method proposed by Asaoka (1978) to back calculate the coefficient of consolidation. On the basis of settlement plot, it was possible to evaluate that value. The horizontal coefficients of consolidation have been evaluated from the followings:

$$C_\mathrm{h} = \frac{-D_\mathrm{e}^2 \cdot F \cdot \ln(\beta_1)}{8 \cdot \Delta t} \qquad (1)$$

where: D_e = diameter of drain influence zone; $F = F(n) + F_\mathrm{s} + F_\mathrm{r}$; $F(n)$ = factor expressing the effect of drain spacing; F_s = factor expressing the effect of smear; F_r = factor expressing the effect of well-resistance; Δt = time interval for settlement plot according to Asaoka (1978) method; β_1 = slope of the settlement plot in terms of the settlement at time t_i and of time t_{i-1} in an arithmetic scale

The final settlement and C_h values were back-calculated by using the Asaoka (1978) graphical method. In addition, using the

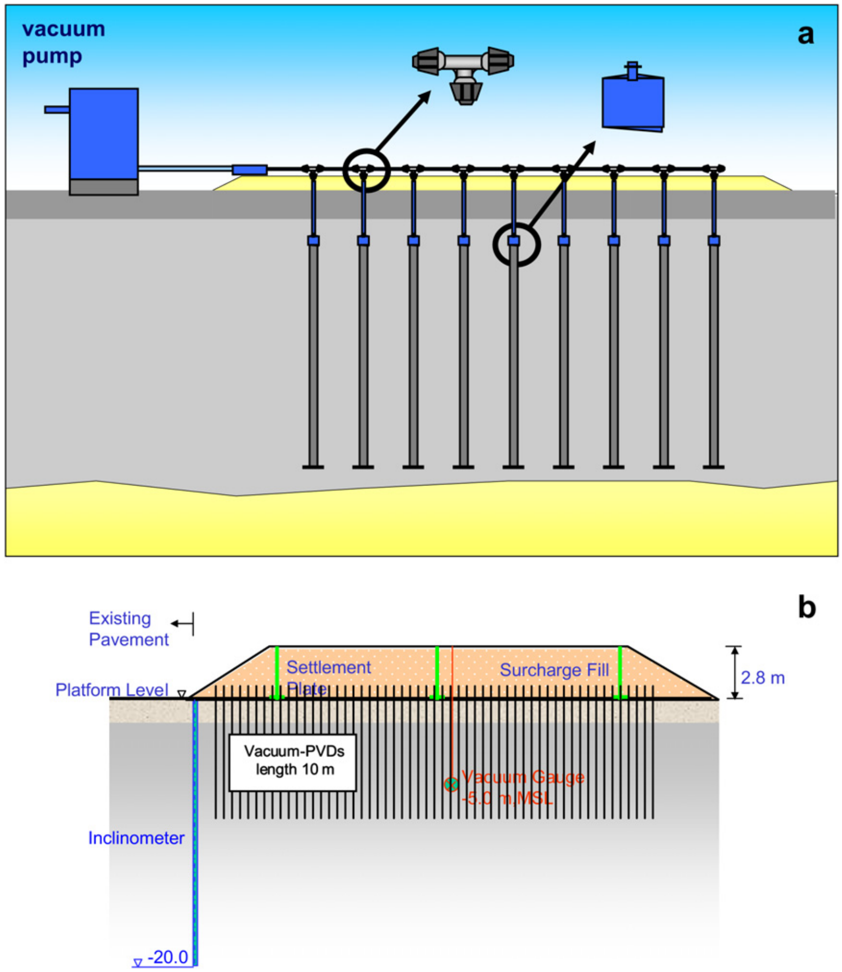

Fig. 6. (a) Cross-section of vacuum-PVDs method. (b) Monitoring instruments of vacuum-PVDs method.

method of Hansbo (1979), C_h is back-calculated from the following relationships at $U_h = 90\%$.

$$U_h(t) = 1 - \exp\left(\frac{-8T_h}{F}\right) \tag{2}$$

where U_h is the degree of consolidation for horizontal drainage; T_h is the time factor for horizontal drainage; F is the factor which expresses the additive effect due to the spacing of the drains, $F(n)$, smear effect, F_s, and well-resistance, F_r, as defined previously. The values of $F(n)$, F_s and F_r are given by the following equations:

$$F(n) = \ln\left[\frac{D_e}{d_w}\right] - \frac{3}{4} \tag{3}$$

$$F_s = \left[\frac{k_h}{k_s} - 1\right] \ln\left[\frac{d_s}{d_w}\right] \tag{4}$$

$$F_r = \pi z(L - z)\frac{k_h}{q_w} \tag{5}$$

where D_e is the diameter of the equivalent soil cylinder, d_w is the equivalent diameter of the drain, k_h is the coefficient of horizontal permeability, k_s is the horizontal permeability of the smear zone, d_s is the diameter of the smear zone, z is the distance from the drainage end of the drain, L is the length of the drain for double drainage and twice the length of the drain for single drainage, q_w is the discharge capacity of the drain at hydraulic gradient of 1 (one). The time factor, T_h, for horizontal drainage can be calculated using:

$$T_h = \frac{C_h t}{D_e^2} \tag{6}$$

where C_h is the coefficient of horizontal consolidation and t is the time elapsed after the application of the load.

In PVDCON, finite element formulation considers the effects of PVDs by modifying 1D continuity equation of consolidation as follows (Chai and Miura, 2000).

$$\frac{k_v}{\gamma_w}\frac{\partial^2(u - p_{vac})}{\partial z^2} - \frac{8k_h(u - p_{vac})}{\gamma_w D_e^2 \mu} + \frac{\partial \varepsilon_v}{\partial t} = 0 \tag{7}$$

$$\mu = \ln\frac{n}{s} + \frac{k_h}{k_s}\ln s - \frac{3}{4} + \pi\frac{2l^2 k_h}{3q_w} \tag{8}$$

where γ_w is the unit weight of water, z is depth, t is time ε_v is volumetric strain, u is excess pore water pressure, p_{vac} is the final vacuum pressures, k_v is hydraulic conductivity in the vertical direction, k_h is hydraulic conductivity in the horizontal direction, l is drainage length, D is the diameter of unit cell, q_w is discharge capacity of PVD, $n = D/d_w$ (d_w is the equivalent diameter of PVD) and $s = d_s/d_w$, k_h, k_s and d_s are defined previously.

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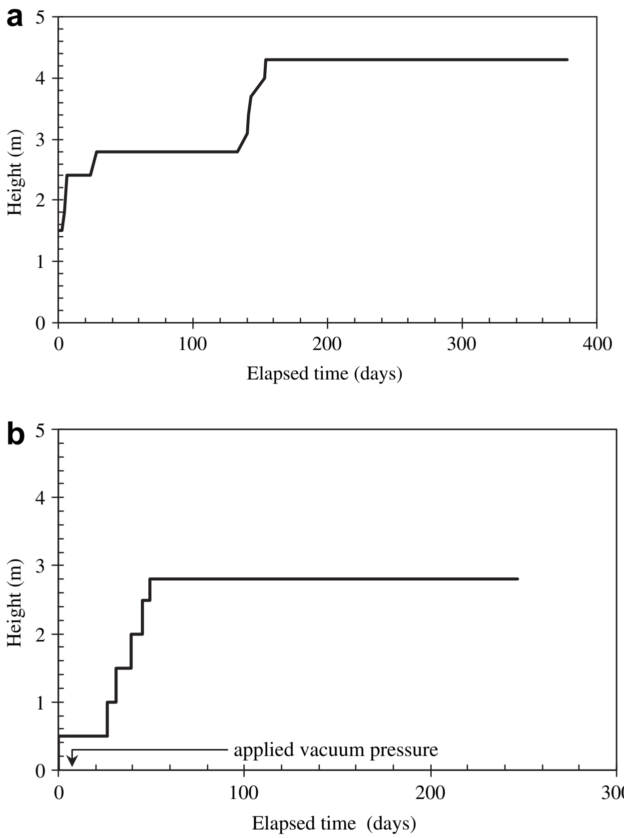

Fig. 7. The load-time of embankment improved with (a) conventional PVDs and (b) Vacuum-PVDs.

4. Results and discussions

4.1. Laboratory results

The final settlements between the PVD improved reconstituted specimen with vacuum preloading and the PVD improved reconstituted specimen without vacuum preloading are shown in Fig. 8. The settlement of the specimen with the vacuum-PVD was considerably faster in consolidation rate than the specimen with only PVD. But the final settlement of both specimens was same which were approximately 23 mm.

The measured and the theoretical (based on Eqs. (2)–(6)) time settlement curves for the reconstituted specimens are shown in Fig. 9a and b for PVD and vacuum-PVD, respectively. The back-calculated values of C_h and k_h/k_s for the specimen with only PVD are 1.08 m^2/yr and 2.70, respectively. For the specimen with the vacuum-PVD, the corresponding values are 1.87 m^2/yr and 2.50, respectively. Consequently, the use of vacuum-PVD increased the permeability of the smear zone resulting in the increase in C_h by 70% and decrease in k_h/k_s of about 7%. As expected the horizontal coefficient of consolidation of reconstituted specimen improved by PVD with vacuum pressure was higher than specimen without vacuum pressure due to higher rate of consolidation compared with PVD only improvement. Thus, the construction rate can be faster with reduction in consolidation time. The settlement prediction (Hansbo, 1979) of laboratory result in the early stages of the settlement, were underpredicted but after 60% of consolidation, the predicted settlement yielded good agreement with the observed settlements for both improvements using PVD with and without vacuum pressures.

Fig. 10a and b show that the percentage of water content reductions and percentage of strength increase were increased with decreasing distances from PVD after PVD improvement with and without vacuum pressure. The vane shear strengths after PVD improvement with vacuum pressure was higher than PVD improvement without vacuum pressure.

4.2. Field test results

The method of Asaoka (1978) for prediction of settlement magnitude and Hansbo (1979) for prediction of settlement rate were combined together to analyze the field observation data of two stations of PVD improved soft ground by surcharge load and the other two stations of PVD improved soft ground with surcharge load combined with vacuum preloading. The measured settlements of those stations were then compared with the predictions. The comparison of settlement behavior using PVD without and with vacuum is plotted with time in Figs. 11 and 12. The PVD with vacuum clearly indicates faster rate of settlements. The values of C_h and k_h/k_s contributed to the time to reach 90% degree of consolidation of PVD improved soft Bangkok clay. The reduction of time to reach the 90% degree of consolidation using surcharge load combined with vacuum pressure was higher than PVDs without vacuum pressure by about 1.4–1.5 times due to the higher values of horizontal coefficient of consolidation.

Fig. 13a shows the measured and predicted settlements at station $X = 14\,012$, $Y = 11\,567–12\,633$ by using PVD with surcharge load. The back-calculated C_h value was 2.03 m^2/yr with k_h/k_s values of 7.0. The final settlement predicted from Asaoka method was 1485.89 mm. Fig. 13b shows the measured and predicted settlements at station $X = 13\,560$, $Y = 11\,567–12\,600$. The C_h value was

Table 6
Parameters related to PVDs with vacuum for settlement analysis.

Item	Unit	Values
Drain Type; CeTeau drain type CT-D911		
Equivalent diameter of the drain, $d_w = (b + t)/2$	mm	51.75
Diameter of the equivalent soil cylinder, $D_e = 1.05S$	m	0.8925
Smear zone diameter, $d_s = 2d_m$	mm	191.49
Hydraulic conductivity ratio, k_h/k_s		2–10
Discharge capacity, q_w	m^3/yr	100

Table 5
Summary of general of soil parameters at SBIA.

Depth (m)	γ_t (kN/m^3)	w_n (%)	σ'_{vm} (kN/m^3)	CR	RR	M	OCR	C_v (m^2/yr)	C_h (m^2/yr)
0–2	18.50	70	45	0.35	0.035	1.2	3.31	1.095	4.380
2–5	13.80	110	37	0.50	0.050	0.9	1.31	1.022	4.088
5–10	14.00	100	59	0.42	0.042	1.0	1.32	1.606	6.424
10–13	15.00	75	100	0.40	0.040	1.2	1.59	1.314	5.256
13–15	15.70	60	110	0.30	0.030	1.2	1.43	1.314	5.256

Table 7
Parameters related to PVDs without vacuum for settlement analysis.

Item	Unit	Values
Drain type; CN (A1)		
Equivalent diameter of the drain, $d_w = (b + t)/2$	mm	51.5
Diameter of the equivalent soil cylinder, $D_e = 1.05S$	m	0.8925
Smear zone diameter, $d_s = 2d_m$	mm	186
Hydraulic conductivity ratio, k_h/k_s		2–10
Discharge capacity, q_w	m^3/yr	1000

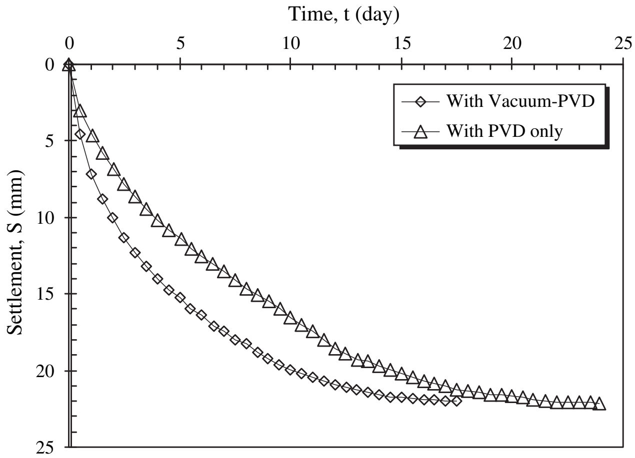

Fig. 8. Settlement-time relationship from large consolidometer of reconstituted sample in the laboratory using PVDs with and without vaccum.

2.31 m^2/yr with k_h/k_s values of 7.4. The final settlement predicted from Asaoka method was 1773.41 mm.

Fig. 14a shows the measured and predicted settlements at station $X = 12\,566.400$, $Y = 12\,570.000$ by using PVD with surcharge and vacuum preloading. The C_h value was 3.21 m^2/yr with k_h/k_s values of 6.2. The final settlement predicted by Asaoka (1978) method was 1356.62 mm. Fig. 14b shows the measured and predicted settlements at another station $X = 12\,566.400$, $Y = 11\,683.50$. The back-calculated C_h value was 3.80 m^2/yr with k_h/k_s values of 7.1.

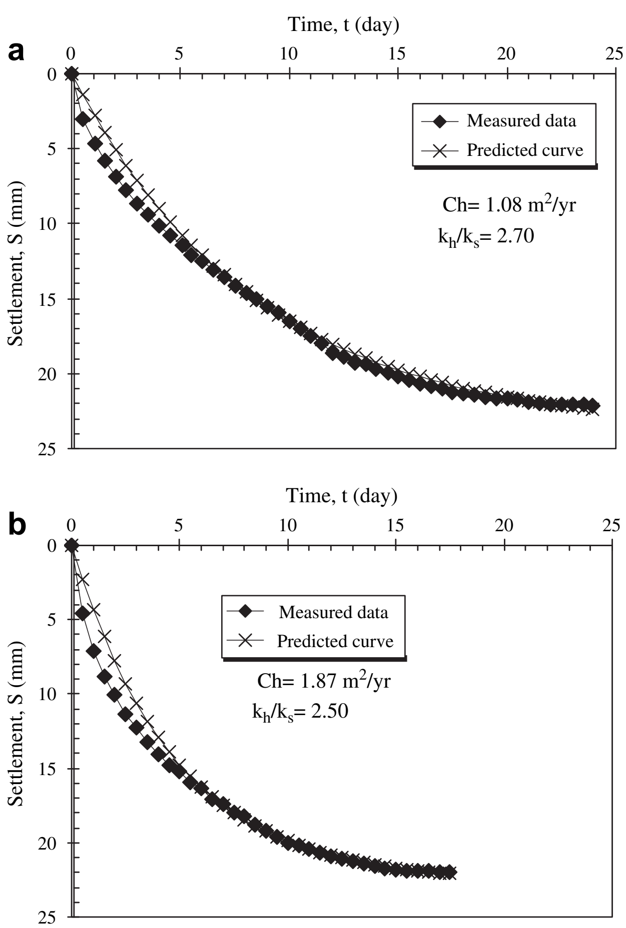

Fig. 9. The observed and fitted curves for settlements to determine C_h values for the reconstituted specimen in large consolidometer (a) with PVD only and (b) with vacuum-PVD.

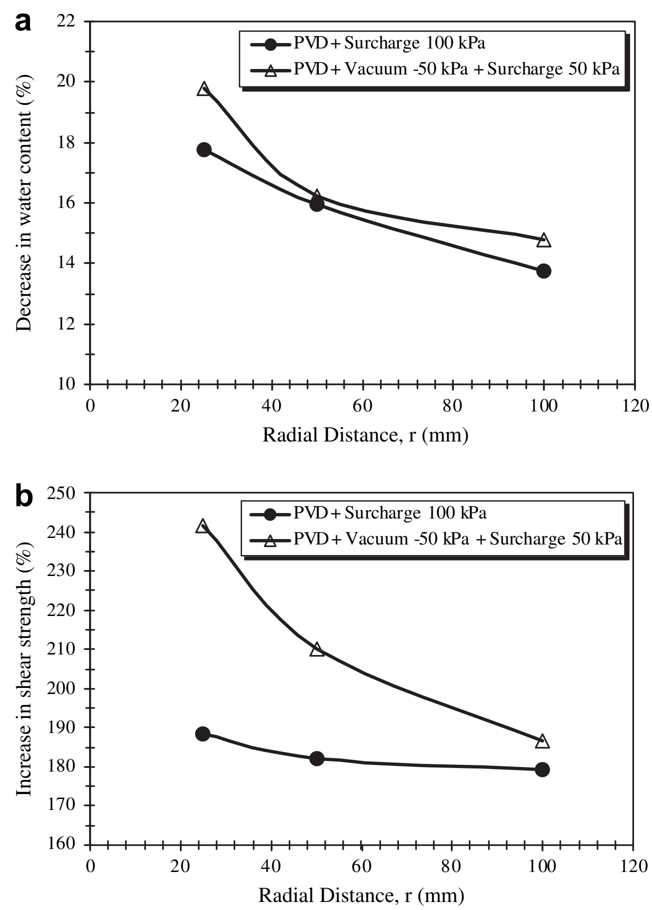

Fig. 10. Reconstituted specimens treated with PVD with and without vacuum pressure after consolidation test of the consolidometer of (a) water content reduction and (b) shear strength increase.

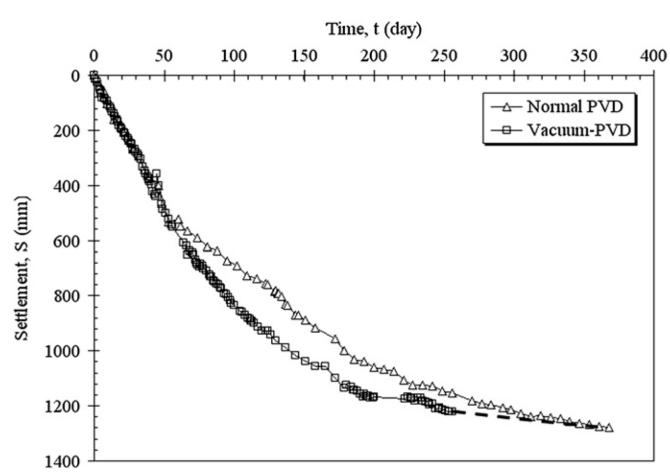

Fig. 11. Comparison of settlement of PVD improvement with and without vacuum pressure (Sta. $X = 14\,012$, $Y = 12\,567–12\,600$ for PVD without vacuum and Sta. $X = 12\,566.4$, $Y = 12\,570.000$ for PVD with vacuum pressure).

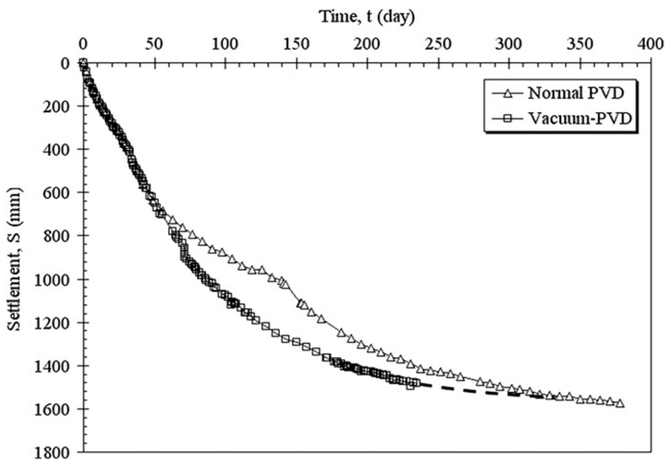

Fig. 12. Comparison of settlement of PVD improvement with and without vacuum pressure (Sta. $X = 13\,560$, $Y = 12\,567–12\,633$ for PVD without vacuum and Sta. $X = 12\,566.4$, $Y = 12\,583.500$ for PVD with vacuum pressure).

The final settlement predicted by Asaoka (1978) method of the station was 1614.94 mm.

Regarding the settlement predicted by using PVDCON software, the results show that the early settlement values were less than the observed field data because the settlements predicted by PVDCON software may include elastic settlement but the observed settlements included only the primary settlements. Thus, the sensitivity analyses of settlement using PVD improvement without and with vacuum are demonstrated by neglecting the elastic settlement using PVDCON software as shown in Figs. 15–18. By varying the

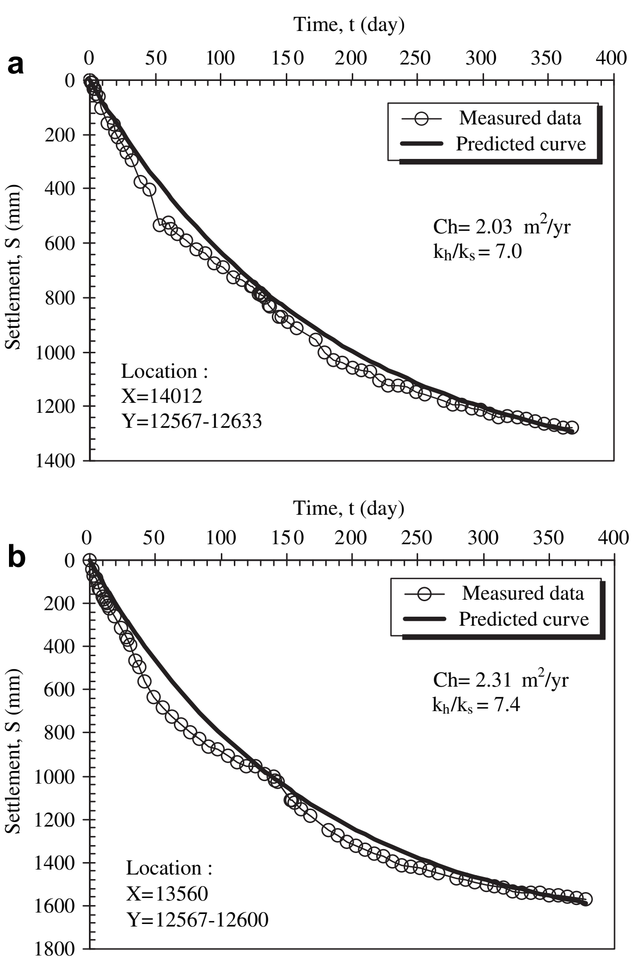

Fig. 13. Back-calculated compressibility parameters of field observations of conventional surcharge load in the field with PVD only (a) $X = 14\,012$ $Y = 12\,567–12\,633$ (b) $X = 13\,560$ $Y = 12\,567–12\,600$.

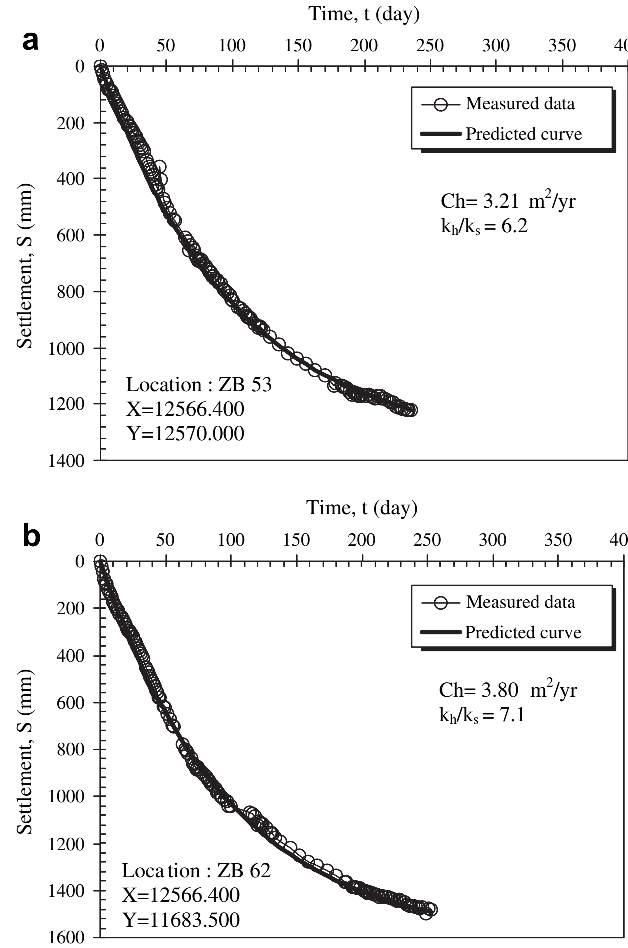

Fig. 14. Back-calculated compressibility parameters of field observations with PVD and combined surcharge and vacuum preloading (a) station ZB 53 (b) station ZB 62.

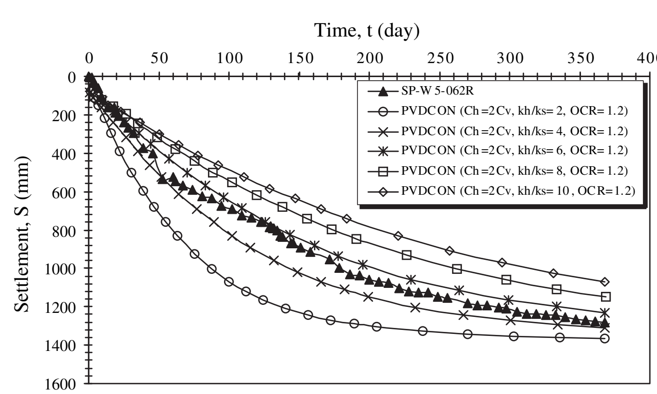

Fig. 15. Comparison of settlement between field observation data and predicted settlement by PVDCON method with PVD only at SBIA site at station: $X = 14\,012$, $Y = 12\,567–12\,633$ (neglect elastic settlements).

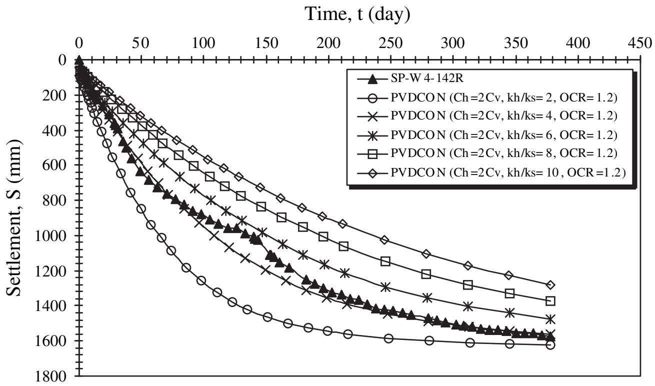

Fig. 16. Comparison of settlement between field observation data and predicted settlement by PVDCON method with PVD only at SBIA site at station: $X = 13\,560$, $Y = 12\,567$–$12\,600$ (neglect elastic settlements).

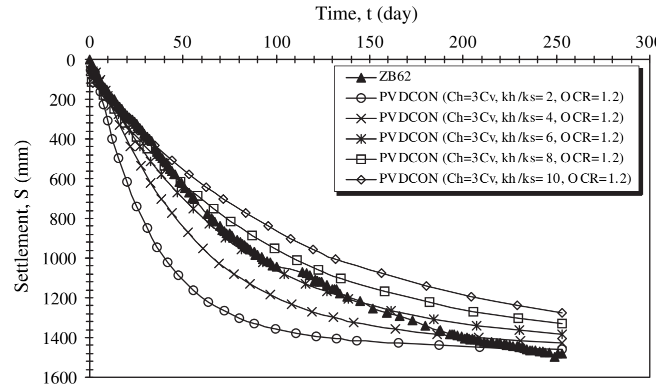

Fig. 18. Comparison of settlement between field observation data and predicted settlement by PVDCON method using PVD with combined surcharge and vacuum at SBIA site at station: ZB62; $X = 12\,566.4$, $Y = 12\,583$ (neglect elastic settlements).

ratios of k_h/k_s and C_h/C_v, using PVDCON software, the results of sensitivity analyses are as follows:

(i) The ratio of horizontal permeability at undisturbed zone to horizontal permeability at smear zone (k_h/k_s) affected the predicted settlement, and by increasing k_h/k_s, the predicted settlement reduced.
(ii) The ratio of horizontal coefficient of consolidation to vertical coefficient of consolidation (C_h/C_v) also effected the predicted settlement. The higher C_h/C_v, the higher the rate of predicted settlement.

For PVD only, at OCR of 1.2, the k_h/k_s of 4–6 and $C_h = 2C_v$ were obtained where $C_v = 1.58$ m^2/year as shown in Figs. 15 and 16. For PVD with vacuum pressure at −60 kPa, and OCR of 1.2, the k_h/k_s of 4–8 and $C_h = 3C_v$ were obtained where $C_v = 1.58$ m^2/year as shown in Figs. 17 and 18. The k_h/k_s values were slightly higher in the later than the former due to slightly larger smear zone as shown in Tables 6 and 7. In summary, the addition of vacuum pressure to PVD seems to increase the coefficient of horizontal consolidation, C_h as expected. The other parameters may not be affected that much, particularly, the permeability ratio, k_h/k_s, because the vacuum preloading seems to increase both the permeabilities of the smeared and the undisturbed zones.

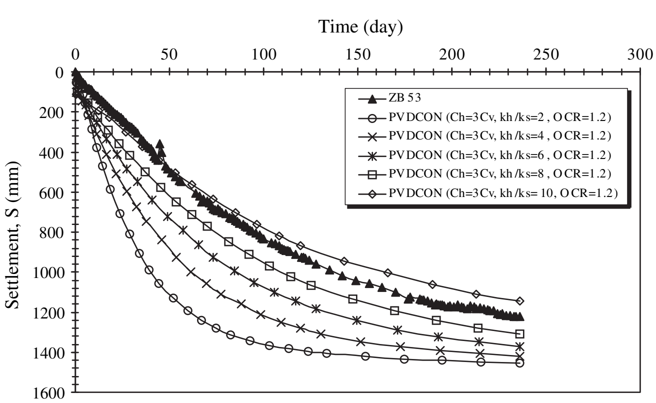

Fig. 17. Comparison of settlement between field observation data and predicted settlement by PVDCON method using PVD with combined surcharge and vacuum at SBIA site at station: ZB53; $X = 12\,566.4$, $Y = 12\,570$ (neglect elastic settlements).

5. Conclusions

Based on the data and results of the analyses, the following conclusions can be made:

1) The back-calculated Ch values of reconstituted specimens in the laboratory tests were 1.08 and 1.87 m^2/yr for PVD only and vacuum-PVD, respectively. The corresponding k_h/k_s values were 2.7 for PVD only and 2.5 for vacuum-PVD.
2) Based from back-calculated results from the field test data, the average C_h values were 2.17 m^2/yr and 3.51 m^2/yr from the PVD only and vacuum-PVD, respectively, and with corresponding k_h/k_s values of 7.2 and 6.6.
3) The surface settlement prediction by Asaoka (1978) graphical method yielded very good predictions for PVD without vacuum preloading but for PVD with vacuum prediction, the predicted settlements were slightly higher than the field observation data.
4) The settlement predicted by PVDCON yielded quite good predictions of surface settlement at the final loading stage but the predicted settlement at the early stage was less than the actual settlement.
5) From sensitivity analyses of field data using PVDCON software, it was found that increasing k_h/k_s values tends to decrease the magnitude of predicted settlements. The values of k_h/k_s at OCR = 1.2 from sensitivity analyses were 4–6 with $C_h = 2C_v$ for PVD only. The corresponding values of k_h/k_s and OCR = 1.2 from sensitivity analyses were 4–8 with $C_h = 3C_v$ for PVD with vacuum.
6) The PVD improved soft ground with combined surcharge load and vacuum preloading reduced the time to 90% degree of consolidation by one-third due to the consequent higher values of the coefficient of horizontal consolidation and subsequent rate of settlements.

Notations

a	width of prefabricated vertical drain (L)
b	thickness of prefabricated vertical drain (L)
C_a	creep coefficient (dimensionless)
C_h	coefficient of horizontal consolidation (L^2/T)
C_v	coefficient of vertical consolidation (L^2/T)
CR	compression ratio (dimensionless)
D_e	diameter of the equivalent soil cylinder (L)
d_s	diameter of the mandrel (L)
d_m	diameter of the smear zone (L)
d_w	equivalent diameter of the drain (L)

F factor which expresses the additive effect due to the spacing of the drains, smear effect, and well-resistance (dimensionless)
$F(n)$ factor expressing the effect due to the spacing of the drains (dimensionless)
F_s factor expressing the effect due to the smear effect (dimensionless)
F_r factor expressing the effect due to the well-resistance (dimensionless)
k_h coefficient of horizontal permeability of the undisturbed zone (L/T)
k_s coefficient of horizontal permeability of the smear zone (L/T)
L length of the drain for double drainage and twice the length of the drain for single drainage (L)
POP effective overburden pressure (F/L^2)
p_{vac} final vacuum pressures (F/L^2)
q_w discharge capacity of the drain at hydraulic gradient of 1 (L^3/T)
RR recompression ratio (dimensionless)
S settlement at time, t (L)
s spacing ratio (dimensionless)
S_f final settlement (L)
T_h time factor for horizontal drainage (dimensionless)
t time elapsed after the application of the load (T)
U_h degree of consolidation for horizontal drainage (%)
w_n natural water content (%)
z distance from the drainage end of the drain (L)
σ'_{vm} maximum past pressure (F/L^2)

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